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FY14 Annual Report

M. A. Stoyer, N. D. Scielzo, C. Y. Wu

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FY14 Annual Report

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Physics Division, LLNL

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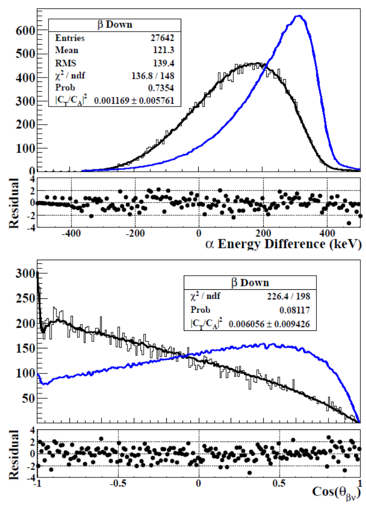

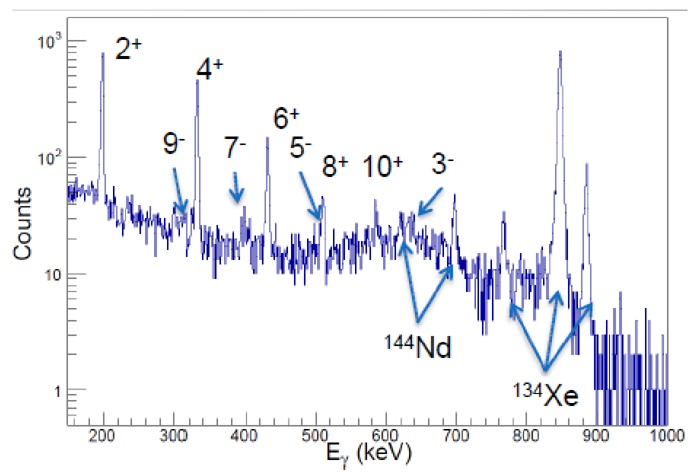

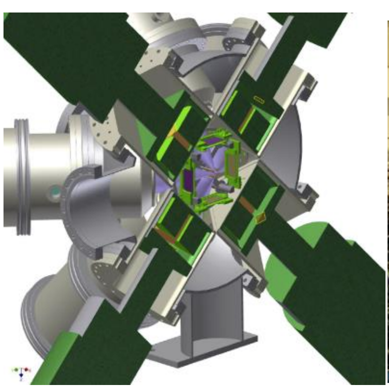

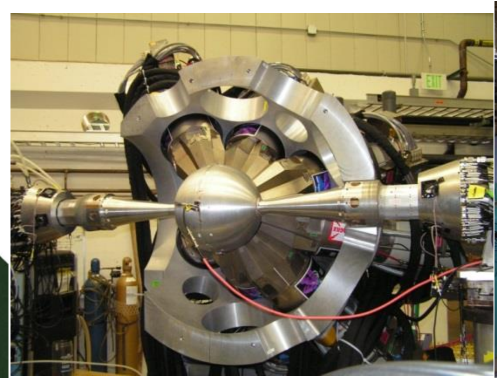

Contents

Investigating nucleosynthesis and the Standard Model with β decay

Abstract

The neutrinos and neutrons emitted in nuclear β decay can be precisely studied using radioactive ions held in a radiofrequency-quadrupole ion trap. The momentum and energy of particles that would otherwise be difficult (or even impossible) to detect can be reconstructed from the momentum imparted to the recoiling nucleus. The β-delayed neutron emission for isotopes of interest for *r*-process nucleosynthesis is being studied. Measurements of β-decay angular correlations, which are sensitive to exotic particles and other phenomena beyond the Standard Model, can be improved by reconstructing the complete decay kinematics of the mirror ^{8}Li and ^{8}B $\beta^{\pm}$ decays.

This research is well aligned with the Nuclear Science Advisory Committee Long Range Plan under NSAC Performance Evaluation Milestones: (1) NA6, part of which is to measure decay properties of selected neutron-rich nuclei in the *r*-process, and (2) FI4, to improve measurements of nuclear β decay to constrain physics beyond the Standard Model.

Recent Accomplishments

The Beta-decay Paul Trap (BPT) [Sci12] was designed and commissioned by N.D. Scielzo and the Canadian Penning Trap collaboration. The BPT has an open electrode structure that allows radiation detectors to surround the trapped-ion cloud. The ions are confined in a volume of ~1 mm^3 using radiofrequency electric fields with peak-to-peak voltages of up to 1 kV at frequencies up to 2 MHz and DC potentials of ~100 V. Typical ion confinement times are >200 s so essentially all short-lived radioactive isotopes decay within the trap.

Beta-delayed neutron spectroscopy can be performed by reconstructing the neutron emission probabilities and energy spectra from the time of flight of the recoiling nuclei, thereby circumventing the difficulties associated with direct neutron detection. This novel approach was conceived of by N.D. Scielzo and was first demonstrated by a LLNL-led team by studying the β decay of ^{137}I ions held in the Beta-decay Paul Trap (BPT) [Sci12]. The time-of-flight spectrum of β-recoil-ion coincidences was measured using a plastic scintillator β detector and a microchannel plate ion detector. The measured neutron branching ratio and energy spectrum were consistent with previous direct measurements and the results were published in Physical Review Letters [Yee13a]. The demonstration of the recoil-ion spectroscopy approach to β-delayed neutron emission was the basis of the PhD thesis [Yee13b] of Ryan Yee, a LLNL-funded graduate student in the Department of Nuclear Engineering at the University of California at Berkeley.

Since that work, several upgrades to the ion trap and detector array were implemented. These upgrades are described in detail in Ref. [Sci14]. New trap electrodes were installed to reduce the electric-field perturbation on the recoil-ion trajectories. The LLNL team led the design, construction, and commissioning of a new detector array consisting of two ΔE-E plastic scintillators capable of stopping ~15-MeV β particles, two position-sensitive ion detectors, and two HPGe detectors. With the new detector array, the coincident detection efficiency was improved by over an order of magnitude, the β-particle energy could be measured, the β-particle and neutron energy thresholds were both lowered to ~50 keV, and the neutron-energy resolution was improved.

In mid-2013, the BPT was relocated to a low-energy CARIBU beamline for a campaign of measurements that were carried out in the beginning of FY14. These measurements took advantage of the high-intensity fission product beams available at CARIBU. Data for $^{137\text{-}138,140}$I, $^{134\text{-}136}$Sb, and $^{144\text{-}145}$Cs were collected in Nov.-Dec. 2013 and are currently under analysis. The time-of-flight (TOF) spectrum of recoil ions following detection of a β particle in the plastic scintillator is shown in Fig. 1 for each measured isotope. This data was collected with the beam intensities available at the time, which ranged from ~10 ions/sec (^{136}Sb) to ~1000 ions/sec (^{137}I). The structure observed at 0.4-2.0 μs is due to recoil ions that receive a larger momentum kick from neutron emission. The neutron energy spectra can be determined from the TOF distribution. This research is the PhD thesis topic for Shane Caldwell in the Department of Physics at the University of Chicago and Agnieszka Czeszumska in the Department of Nuclear Engineering at the University of California at Berkeley.

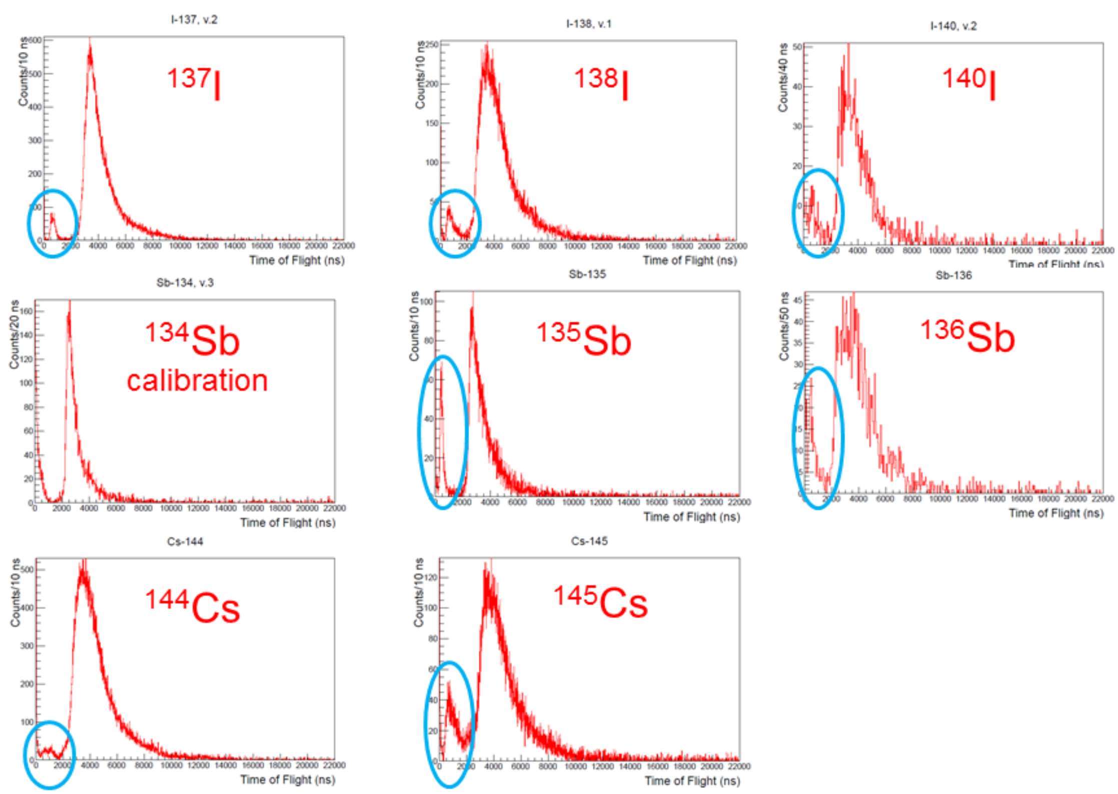

Fig. 1: The TOF spectra for the data collected recently at CARIBU. The higher-energy recoils at ~0.5 μs from neutron emission (circled in blue) are clearly separated from the lower-energy recoils peaked at ~3-4 μs. Analysis of this data is underway. The neutron-energy spectrum obtained here compares favorably with directly-measured results.

Measurements of β-decay angular correlations can be made by taking advantage of the unique properties of the ^{8}Li and ^{8}B β decays and the benefits afforded by using trapped ions to allow an accurate determination of the direction and energy of each emitted neutrino. A successful proof-of-principle measurement of the α-β-ν angular correlation in the β decay of ^{8}Li that places a limit of 3.1% (at 95.5% confidence level) on any non-Standard Model tensor contribution to the decay was also recently performed with the BPT and published in Physical Review Letters [Li13]. For this work, the trapped ions were surrounded by four sets of position-sensitive silicon detectors. The momentum direction of the β particle and the momentum and energy of the break-up α particles were determined which provides enough information to reconstruct the neutrino energy and momentum for each β-α-α coincidence.

The detector array for these measurements has since been upgraded. New double-sided silicon strip detectors (DSSSDs) with thinner dead layers, larger areas, and finer segmentation have been installed. For ^{8}Li, an order of magnitude higher statistics than the original work [Li13] have been collected using this new detector array. The latest ^{8}Li campaign data has been fully analyzed and will determine the β-ν angular correlation with a precision of ~1%. This will be the first improvement in 50 years of the limit set by Johnson and collaborators [Sum07] on a possible intrinsic tensor component in the electroweak interaction. The manuscript summarizing this result is in the process of being submitted to Physical Review Letters [Ste14]. This work was the PhD thesis research of Matthew Sternberg in the Department of Physics at the University of Chicago [Ste13].

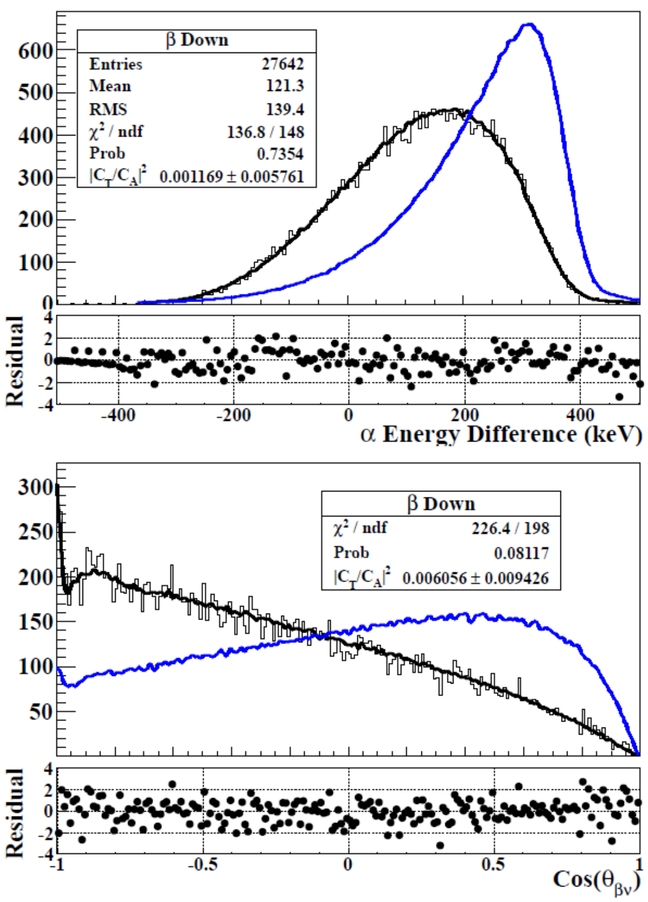

Fig. 2: Top: Energy difference spectra from α particles detected on the top-bottom detector pair when the β particle is detected on the bottom detector. Bottom: The reconstructed $\cos(\Theta_{\beta\nu})$ spectrum for the same events. The smooth black curve is the fit to the data and the smooth blue curve is the distribution expected for a pure tensor interaction.

In July 2014, the first experimental campaign with trapped ^{8}B was completed. The comparison of angular correlations coefficients of the mirror decays of ^{8}Li and ^{8}B is needed to interpret recoil-order contributions as part of our program to test fundamental symmetries of the Standard Model. As a result of the improvements to the production and transport systems implemented since the previous ^{8}Li run, the observed data rate and total statistics collected in the ^{8}B campaign were comparable to our latest ^{8}Li run even though ^{8}B is much more difficult to produce. There were $\sim 10^6$ α-α coincidences and $\sim 3\times10^5$ β-α-α coincidences detected and a fractional precision of <1% on the decay correlations is expected from this data set. Analysis of the ^{8}B data set is currently underway.

In addition, calibration measurements using trapped ^{20}Na ions are underway. The broad α spectrum from the breakup of the ^{8}Be first excited-state peaks at 1.45 MeV making ^{20}Na, which emits β-delayed α particles at energies down to 2.2 MeV, a good candidate for calibrating this hard-to-reach energy region. This method of calibrating the silicon detectors under nearly identical operating conditions to the ^{8}Li and ^{8}B measurements will reduce one of the main contributors to the systematic uncertainty in the β-decay correlation measurements.

Recognition

These precision β-decay studies using trapped ions were recently highlighted in both LLNL's FY13 Performance Evaluation Report to the Lab Director and LLNL's FY13 Science and Technology Annual Report summarizing the year's high-profile accomplishments. This effort was also recognized with a LLNL Directorate Award in Science and Technology for "the development of novel ion trap techniques to infer the energy and direction of (1) neutrons and (2) neutrinos from studies of the nuclear recoil." In FY14, N.D. Scielzo was invited to give talks at Michigan State University (January 2014), University of Notre Dame (February 2014), Texas A&M University (March 2014), Argonne National Laboratory (May 2014), and the Solvay Institutes in Brussels, Belgium (September 2014).

ATLAS/CARIBU Beam Time

This program has been well received by the ATLAS Program Physics Advisory Committee (PAC) which decides how beam time is allocated. N.D. Scielzo has been PI/co-PI on 4 ion-trap proposals in the last 2 years that have been awarded a total of 47 days of Priority 1 beam time (the full request) at these facilities. Three additional proposals with LLNL members as PI or co-PI were submitted to the August 2014 ATLAS call for proposals to pursue further β-decay measurements of ^{8}Li and fission products using the ion trap and detector arrays developed here.

Future work

The neutrinos and neutrons emitted in nuclear β decay can be precisely studied using radioactive ions held in a radiofrequency-quadrupole ion trap. The momentum and energy of particles that would otherwise be difficult (or even impossible) to detect can be reconstructed from the momentum imparted to the recoiling nucleus. The β-delayed neutron emission for isotopes of interest for *r*-process nucleosynthesis will be studied. Measurements of β-decay angular correlations, which are sensitive to exotic particles and other phenomena beyond the Standard Model, can be improved by reconstructing the complete decay kinematics of the mirror ^{8}Li and ^{8}B $\beta^{\pm}$ decays.

A dedicated ion trap that is optimized for β-delayed neutron spectroscopy will be developed. The design of the new trap and detector array will be guided by the analysis of results obtained with the BPT using CARIBU beams. The analysis of the data for $^{137\text{-}138,140}$I, $^{134\text{-}136}$Sb, and $^{144\text{-}145}$Cs will be completed and the analysis tools and experience will be used to guide the design of the detector array. The approach will be applied to study isotopes near the N=82 neutron magic number of importance to *r*-process nucleosynthesis. With CARIBU, many of these isotopes will be delivered to the low-energy beamline in intensities 10^{2}-10^{5} ions/s. The isotopes $^{132\text{-}133}$In, $^{134\text{-}136}$Sn, $^{135\text{-}138}$Sb, and $^{139\text{-}140}$Te will be studied and many of these isotopes have large P_n values (>20%) and have either never been measured or have been measured once.

To achieve the precision needed for stringent tests of the SM using ^{8}Li and ^{8}B, a number of upgrades to the approach will be implemented. Estimates of the achievable statistical and systematic uncertainties for these measurements have been made by comparing the existing ^{8}Li results to Monte Carlo simulations. It is anticipated that the sensitivity to $|C_T/C_A|^2$ can be improved by an order of magnitude (to 0.1%) and that a ~1% measurement of the weak-magnetism term and comparable limit on the induced-tensor term can be achieved.

It is anticipated that funds will be carried over into FY15 sufficient to ensure continued operation during October 2014 and to support the research of the postdoctoral researchers and graduate students working with the LLNL team. The future work described in this section is contingent upon funding of the proposal submitted in May 2014.

Searching for neutrinoless double-beta decay with the CUORE bolometer array

Many of the biggest questions in particle and nuclear physics revolve around our limited knowledge of the properties of the elusive subatomic particle, the neutrino. The discovery of neutrinoless double beta decay (0νDBD), a long sought-after nuclear transition in which two neutrons in a nucleus are converted into two protons and two β particles without the emission of accompanying neutrinos, could have far-reaching scientific consequences by determining not only the neutrino mass and hierarchy but also whether the neutrino is its own antiparticle and therefore whether nature violates the conservation of total lepton number. Lepton-number violation is thought to hold the key to explaining the predominance of matter over antimatter in the universe.

The Cryogenic Underground Observatory for Rare Events (CUORE) is an experiment that will search for the 0νDBD of ^{130}Te and other rare and exotic decays using a large array of cryogenic bolometers. The CUORE experiment brings together about 150 American and European scientists to build and operate an array of 988 cryogenic TeO_2 bolometers - this will be the largest (~ ton) cryogenic bolometer array ever realized. The development of this detector array builds off of the experience with CUORICINO, an array of 62 TeO_2 bolometers with a total mass of 40 kg that completed data taking in 2008.

In FY14, the LLNL group completed an investigation of a source of background that is poorly characterized in CUORE: cosmogenic activation of TeO_2. This process occurs at sea-level during transportation of the TeO_2 bolometers from their production-site in Shanghai, China to the experiment-site in Gran Sasso, Italy. Existing cross-section data is insufficient to reliably estimate this background. The cosmic-ray induced backgrounds that can be expected in the CUORE experiment were determined by performing a series of irradiations of Te and TeO_2 using high-energy protons at CERN [Bar13a] and neutrons of energies up to 800 MeV from LANSCE that simulate the cosmic-ray neutron energy spectrum [Wan14a,Wan14b]. Analysis of the radionuclides produced revealed that ^{110m}Ag will dominate the cosmogenic activation background in CUORE. Estimations using the measured cross section for ^{110m}Ag indicate this source will be negligible compared with other contributions to the CUORE background. Overall, the backgrounds from activation products were found to be at least two orders of magnitude smaller than the background goal of 0.01 counts/(keV·kg·yr) at 2.5 MeV. This effort was the PhD thesis research for Barbara Wang in the Department of Nuclear Engineering at the University of California at Berkeley [Wan14b].

Members of the US CUORE Collaboration from LLNL, UC Berkeley, and the University of South Carolina are currently conducting R&D to investigate the feasibility of using enriched TeO_2 crystals in a next-generation CUORE double-beta decay experiment. As the raw material (enriched ^{130}Te metal) is extremely expensive and in limited supply, it is crucial that the crystal production technique maximize the yield (defined as kg of crystal produced from kg of metal) and preserve the enrichment level. Existing crystal growth incorporates ~25% of the original Te metal into bolometers, with the rest being discarded along the production process. In order to minimize the amount of material consumed during R&D tests, a sample of low-enriched material has been made from natural tellurium in which a small quantity of enriched ^{130}Te is added to produce a larger sample of slightly enriched material. This low-enriched sample will be sufficient for the initial R&D as even this lower level of enrichment can be easily monitored using high-resolution ICP-MS.

For the first pass at increasing the efficiency of the crystal production, three TeO_2 crystals, each enriched to 40%, were recently grown in collaboration with the Shanghai Institute of Ceramics Chinese Academy of Sciences (SICCAS). The procedures used to grow these crystals were modified from those used to produce crystals for the CUORE experiment to increase the crystal yield. Two of the crystals were produced following the CUORE protocol up through the first crystal-growth stage. The leftover material from the two crystals was then used to grow a third crystal.

Cryogenic testing was performed in Hall C of the Laboratori Nationali del Gran Sasso (LNGS) to determine the bolometric performances and radio-purities of these crystals. Inductively-coupled plasma mass spectrometry (ICPMS) was also used analyze the impurity concentrations of various isotopes in the crystals. In comparison with past CUORE crystals, the enriched crystals did not perform as well as bolometers and had higher levels of ^{238}U and ^{232}Th contamination. The energy resolutions of the enriched crystals were ~9 keV at 2615 keV, compared with ~5 keV in CUORE. This difference could be due to elevated levels of Fe, determined to be 2-3 ppm by ICPMS, in the enriched crystals, which lead to increases in the heat capacity at cryogenic temperatures. The bulk ^{238}U and ^{232}Th contamination levels were determined from α-decay lines observed in energy spectra collected during the cryogenic testing. Upper limits on the contamination were determined to be $\sim 2\times10^{-12}$ g/g for ^{238}U and ^{232}Th. These values are ~10 times higher than both the levels seen in CUORE crystals. Additional research is underway to determine if the radiopurity and bolometric requirements can be met with a modified crystal growth protocol that increases the efficiency of incorporating enriched metal into bolometers.

Evolution of shell structure and collectivity in neutron-rich nuclei

Several accomplishments have been made in FY14 toward the project goals on the evolution of shell structure and collectivity in neutron-rich nuclei. We have published the results on the sub-barrier Coulomb excitation study of the one-neutron halo nucleus, ^{11}Be, providing the most precisely measured E1 strength between bound states. We have completed a measurement of the octupole collectivity of ^{144}Ba using CARIBU/GRETINA/CHICO2 at Argonne National Laboratory (ANL). This is a major milestone for CARIBU/GRETINA/CHICO2 in the study of the γ-ray spectroscopy of radioactive neutron-rich nuclei. The CHICO2 performance was flawless during this experiment and others. In addition, the GRETINA/CHICO2 setup is used for γ-ray spectroscopy of fission fragments from a ~ 8-μCi ^{252}Cf source whenever it is not being used for in-beam experiments. We also provided support for the experiments proposed by our collaborators using GRETINA/CHICO2. For the coming fiscal year, we would like to finish the data analysis of ^{144}Ba and complete the measurement of the octupole collectivity of ^{146}Ba as well as support the experiments proposed by our collaborations involving CHICO2.

In addition to our effort at ANL, we have begun to implement our long-range plan to study the shell evolution of neutron-rich nuclei, using the ReA facility at Michigan State University (MSU), by installing the Bambino2 detector system as an auxiliary charged-particle detector for SeGA. Bambino2 has been successfully tested using a ^{252}Cf source of ~ 0.5 μCi. For the coming fiscal year, we will continue the handshaking test of the data acquisition system for the coupling between SeGA and Bambino2 using the same ^{252}Cf source without resorting to the beam and start the research program.

The details of each achievement are described in the sections below.

The E1 strength in the one-neutron halo nucleus, ^{11}Be

^{11}Be ($T_{1/2}$ = 13.8 s) is interesting not only because the parity of the ground state and the only excited state is inverted from what is expected from the traditional shell model, but also because strong E1 strengths have been observed between bound states and from the ground state to the continuum due to its halo structure. The B(E1) value of 0.116(12) e^2fm^2 (0.36 W.U.) was derived from the mean lifetime of 166(15) fs deduced from a Doppler shift attenuation measurement [Mil83]. This B(E1) also was measured using the intermediate-energy Coulomb excitation [Ann95,Fau97,Nak97] and has a weighted average value of 0.105(7) e^2fm^2, determined from a model-dependent analysis using the Extended Coupled Discretized Continuum Channels method (XCDCC) [Sum07,Sum06].

The precision of this B(E1) value between bound states was improved by a factor of ~ 5 from our recent measurement using the sub-barrier coulomb excitation. The experiment was carried out using TIGRESS/Bambino at TRIUMF/ISAC2 with the ^{11}Be beam at two bombarding energies of 19 and 23 MeV on a ^{196}Pt target of 2.92 mg/cm^2. The beam intensity was about 1 – 2 x 10^6 pps sustained over a period of two weeks. The B(E1) value of 0.102(2) e^2fm^2 was determined using the code, Gosia [Czo83], a semiclassical approach and a value of 0.098(4) e^2fm^2 was determined using the XCDCC method [Sum07,Sum06], a quantum mechanical approach with an extended nuclear wavefunction described by a classical cluster model [Nun96]. This precisely measured B(E1) will help test the formulation of the three-nucleon force in the Hamiltonian of the No-Core Shell Model with the Continuum approach [Bar13b,Bar13c], which in turn will improve the predictive power for the nuclear structure of nuclei in the low mass region. The results have been published in Ref. [Kwa14].

The evolution of the octupole collectivity in ^{144,146}Ba

The dominant collective mode of motion exhibited in nuclei is resulting from reflection-symmetric shapes that arise from the quadrupole degree of freedom. However, nuclei with proton numbers near 34, 56, 88, and neutron numbers near 34, 56, 88, 134, can assume reflect-asymmetric shapes that arise from the octupole degree freedom [But96]. The even-odd staggering of the positive and negative parity yrast bands in even-even nuclei, the parity doublets in odd-mass nuclei, and the enhanced E1 strength due to a displacement between the center of charge and mass are among the identifiable phenomena associate with the reflect-asymmetric shapes. Nevertheless, the only observable that provides the unambiguous evidence for an enhanced octupole collectivity is the measurement of E3 strength since the enhanced E1 is sensitive to the shell corrections [But91]. In most cases, the E3 strengths can only be measured by using the sub-barrier Coulomb excitation method.

The neutron-rich Ba isotopes ($Z = 56$, $N \sim 88$) are among the ideal candidates to study the evolution of octupole collectivity in nuclei and can be accessed conveniently using spontaneous fission sources [Phi86,Ham95]. The characteristics of octupole collectivity has been observed in ^{144}Ba ($T_{1/2}$ = 11.5 s) and ^{146}Ba ($T_{1/2}$ = 2.22 s) from the measured even-odd staggering of positive and negative parity bands, however, the measured E1 in ^{146}Ba is an order of magnitude lower than that in ^{144}Ba. The less-enhanced E1 in ^{146}Ba can be attributed to significant shell corrections [But91]. The study of the E3 strengths is the only way to resolve this anomaly. The recently completed CARIBU facility at ANL is the ideal place to study of the evolution of octupole collectivity in the neutron-rich Ba isotopes, produced in the spontaneous fission of ^{252}Cf. A proposal to measure the E3 strengths in ^{144}Ba using the sub-barrier Coulomb excitation method was approved and fielded at the CARIBU facility in FY13. The deexcitation γ rays were observed by (Digital)Gammasphere (DGS) together with the newly upgraded charge-particle detector array, CHICO2 [Wu11], a pixelated parallel-plate avalanche counter for the charged-particle detection. The experiment was aborted due to the inability to produce a sustainable ^{144}Ba beam. A second ^{144}Ba experiment with a bombarding energy of 650 MeV on a ^{208}Pb target of 1 mg/cm^2 was carried out using GRETINA/CHICO2. The experiment was fielded successfully with the beam intensity up to 8,000 pps over a period of 3 weeks in May and June 2014. The setup of GRETINA/CHICO2 is shown in Fig. 3 and the preliminary γ-ray spectrum with corrections for the Doppler shift and γ-ray energy tracking is shown in Fig. 4. The data analysis of the ^{144}Ba data is carried out at LLNL and is expected to finish in the coming fiscal year. We also plan to complete the measurement for ^{146}Ba in the coming fiscal year.

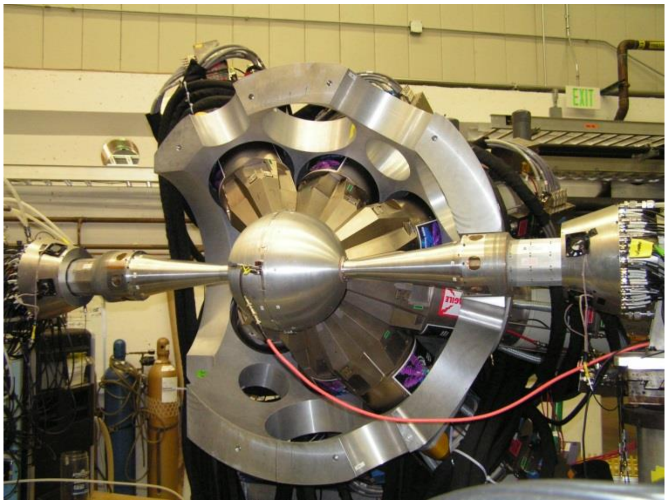

Fig. 3: GRETINA/CHICO2 setup at ANL. GRETINA has 7 detectors installed.

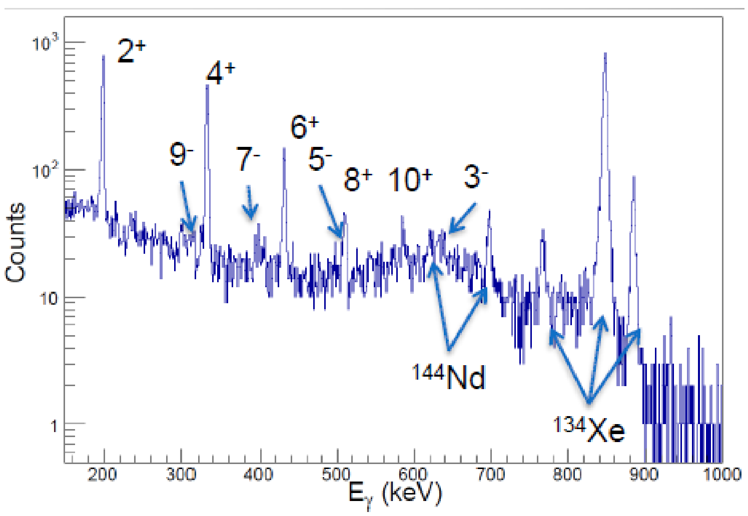

Fig. 4: The preliminary γ-ray spectrum corrected for the Doppler shift and the γ-ray energy tracking. The deexcitation γ rays from the beam contaminants of ^{144}Nd and ^{134}Xe are visible in the spectrum.

CHICO2, a pixelated parallel-plate avalanche counter

CHICO (Compact Heavy Ion COunter) is a highly segmented parallel-plate avalanche counter [Sim00], designed specifically for Gammasphere as an auxiliary detector for the charged-particle detection with a solid-angle coverage of 69% of 4π. It was designed and constructed at the University of Rochester between 1994 and 1996 under NSF funding. A total of 26 experiments were fielded between 1996 and 2008, involving 58 experimentalists from 17 institutions and resulting 37 publications and 5 Ph.D.'s. The last Ph.D. was granted to Adam Hayes from University of Rochester in 2005. Many issues related to nuclear structure physics were addressed by those experiments using Coulomb excitation, quasi-elastic or deep-inelastic reactions, and fission. By measuring their quasi-two-body kinematics, the precise Doppler-shift corrections can be applied for the coincident γ rays observed by Gammasphere, resulting in a γ-ray energy resolution $\sim$ 1%.

With the advent of modern γ-ray energy tracking arrays such as GRETINA, the γ-ray energy resolution can be improved by a factor 2 to 3 by developing an auxiliary detector system with matching position resolution. A proposal to upgrade CHICO to CHICO2 by improving the position resolution, in particular the ϕ resolution from $\sim 9^o$ to $\sim 1^o$, was submitted to DOE and approved in FY10. This improvement was made possible by pixelating the position-sensing cathode board and was completed in FY13 together with a new generation fast amplifiers as well as a new VME based data acquisition system. CHICO2 was successfully integrated into DGS in FY13 and achieved a position resolution of 0.7^o ($1\ \sigma$) in θ and 1.7^o in ϕ. The integration to GRETINA was made successfully in February 2014. The performance was checked using a ^{252}Cf source and the results are shown in Fig 5.

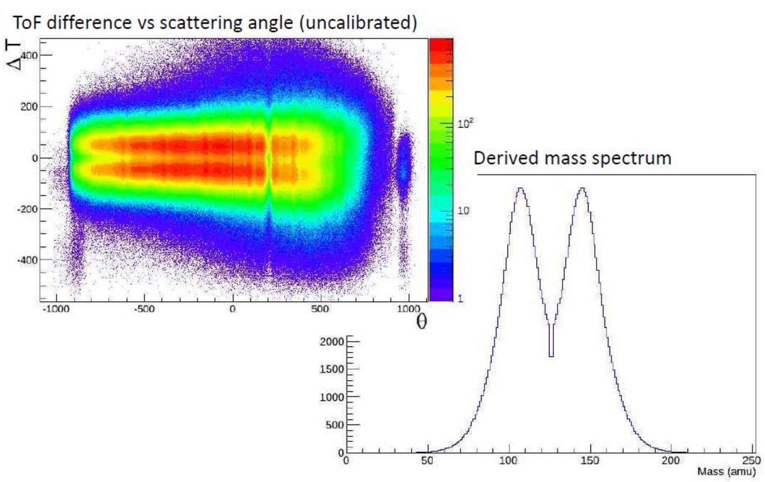

Fig. 5: Measured time-of-flight difference vs. the scattering angle between two fission fragments together with the derived fission-fragment mass spectrum is shown. A mass resolution of $\sim$ 5 amu was obtained with the achieved time and position resolutions.

SeGA/Bambino2 setup at MSU

With the valuable experience accumulated in our initial effort at TRIUMF/ISAC2, we made a transition to study the evolution of shell structure in new territories of isotopes with extreme isospin in the upcoming reaccelerated radioactive beam facility, ReA, at MSU. We have formed a new collaboration with Prof. Alexandra Gade to initiate a sub-barrier Coulomb excitation program with a focus on the study of quadrupole collectivity beyond the first excited state and shape coexistence in nuclei to advance our knowledge on the evolution of nuclear shell structure and collectivity. Two Letters of Intent have been submitted to PAC-34 and PAC-38, respectively, for this new initiative and were well received by the PAC with the instruction that a formal proposal should be submitted once the ReA facility is ready for the radioactive beam.

For the proposed program, we plan to measure the deexcited γ rays using the SeGA array [Mue01] in coincidence with the detection of the scattered particles by a pair of double-side segmented silicon detectors, Bambnio2. This charged-particle detector array has a very similar design to that of Bambino which was used at TRIUMF/ISAC2. Again, it was designed and built in LLNL. The current SeGA array consists of 16 32-fold segmented Ge detectors and is arranged in a barrel configuration around the beam pipe that accommodates Bambino2. In this SeGA/Bambino2 setup, shown in Fig. 6, the detection efficiency reaches about 7.4% for 1-MeV γ rays. The silicon detectors were segmented into 24 rings and 32 sectors with a similar angular resolution to that for CHICO and are placed about 3 cm away from the target with a an angular coverage of 20.1^{o} to 49.4^{o} for the forward hemisphere and 131.6^{o} to 159.9^{o} for the backward hemisphere.

Fig. 6: The SeGA/Bambino2 setup; Two double-side segmented Si detectors are mounted inside a beam pipe surrounded by 16 32-fold segmented Ge detectors in a high-efficiency barrel configuration. The support frame for the SeGA array is installed without the Ge detectors mounted yet.

The test of Bambino2 was completed using a ^{252}Cf source of ~ 0.5 μCi in May 2014. The test for the performance of SeGA/Bambino2 using the ^{252}Cf source is scheduled later in the calendar year of 2014. We expect to field experiments with reaccelerated radioactive beams in the coming fiscal year.

Shape coexistence in ^{72}Ge and ^{76}Ge

This effort is led by M. Albers of ANL and the goal is to study the shape coexistence in ^{72}Ge and ^{76}Ge in terms of the electromagnetic properties of the low-lying states measured using the sub-barrier Coulomb excitation. Experiments were fielded using GRETINA/CHICO2 at ANL by bombarding ^{72}Ge and ^{76}Ge at 308 and 318 MeV, respectively, on a ^{208}Pb target of 0.5 mg/cm^2. The data analysis is carried out at ANL with our help to extract the transitional and static quadrupole moments using the code of Gosia [Czo83] and is expected to finish in the coming fiscal year. Some of the results from the early analysis are shown in Fig. 7 and 8.

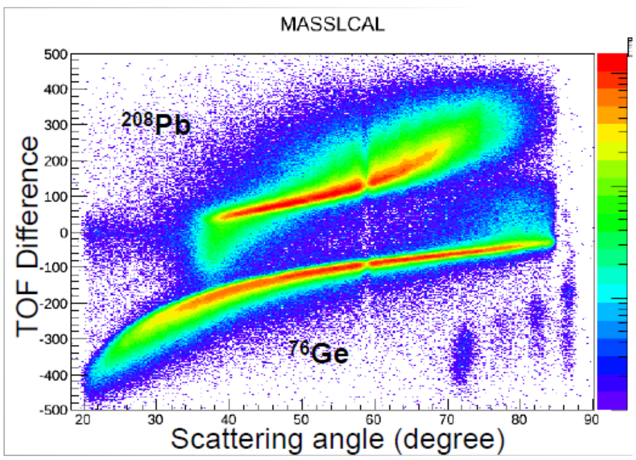

Fig. 7: The time-of-flight difference between the scattered and recoiling particles detected by CHICO2 vs the scattering angle is shown. The particle identity is clearly recognized in this experiment.

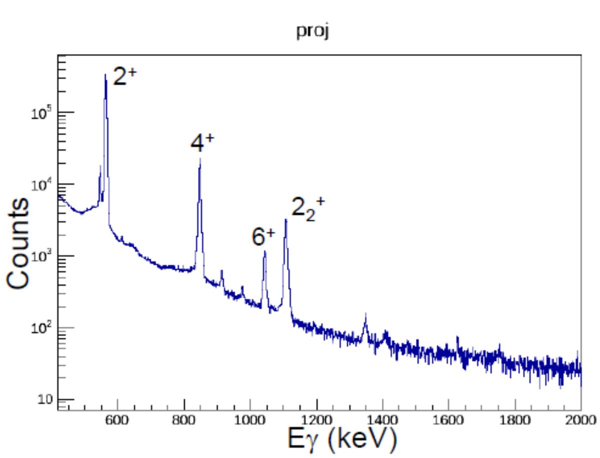

Fig. 8: The preliminary γ-ray spectrum of ^{76}Ge with the Doppler-shift correction integrated over the scattering angle between 40 and 85 degrees.

Future work

The research described here focuses on the nuclear structure with emphasis on two subjects: (a) the evolution of shell structure and collectivity and (b) the isospin dependence of three-nucleon interactions. We approach these studies by exploring the electromagnetic properties in nuclei toward the limits of existence, such as the transition probabilities and static moments using the sub-barrier Coulomb excitation method. We plan to provide the experimental data on those two subjects to enhance our understanding of the nucleus and to improve the predictive power of nuclear models.

We plan to continue our focus on the evolution of shell structure by extending the study to new territories of neutron-rich isotopes with N near 28 using SeGA/Bambino2 at MSU. The development of quadrupole collectivity for nuclei in the vicinity of ^{44}S was attributed initially to the breakdown of the N = 28 shell closure. However, the observation of the Z = 16 sub-shell closure complicates this interpretation. We propose to measure the electromagnetic properties beyond the first excited state such as the shapes of excited states and the rotation-like band structure for heavy sulfur isotopes. This will provide the complementary data important to further our understanding of nuclear structure in this mass region of nuclei, in particular, issues related to the weakening of the N = 28 shell closure.

Secondly, we will begin to explore the isospin dependence of three-nucleon interactions. The inclusion of three-nucleon interactions has been shown to be necessary in the *ab-initio* calculations of nuclear properties, particularly for the light nuclei. We propose to study this subject by exploring the electromagnetic properties of the mirror nuclei with A =10, ^{10}Be and ^{10}C, using Bambino at TRIUMF/ISAC2. Specifically, we propose to measure the static quadrupole moments in addition to the transition probabilities for the first excited states in both nuclei. It provides the data needed to test and further improve the formulation of three-nucleon interactions in the Hamiltonian used in *ab initio* calculations such as the No-Core shell model or the Green's Function Monte Carlo method.

On the subject of the evolution of nuclear collectivity, we will continue the work on the octupole collectivity in the neutron-rich Ba isotopes. In addition, we propose to study the shape transition and shape coexistence in neutron-rich nuclei with A near 100, by exploring the electromagnetic properties beyond the first excited state using the sub-barrier Coulomb excitation method with either DGS or GRETINA /CHICO2 at ANL. For the A $\sim$ 100 region of nuclei, the valence nucleons begin to fill the $h_{11/2}$ neutron and $g_{9/2}$ proton orbitals and their nuclear structures are very sensitive to the occupancy level of those single-particle configurations. It is the ideal testing ground for various nuclear structure models, including the nuclear density functional theory. The PI leads an initial effort to study the nuclear structure of ^{96}Y and ^{98}Y as well as their long-lived and quadrupole deformed isomers.

It is anticipated that funds will be carried over into FY15 sufficient to ensure continued operation during October 2014. The future work described in this section is contingent upon funding of the proposal submitted in May 2014.

Exploring the limits of nuclear stability by producing the heaviest nuclei

This task was funded at the $50K level in FY14, essentially to aid in travel for the P.I., Mark A. Stoyer. This funding was critical. All of these activities enabled continued leadership within the super heavy element scientific community. It enabled the following travel to be accomplished:

M.A. Stoyer attended the first International African Symposium on Exotic Nuclei (IASEN2013) Dec. 2-6, 2013 held in Capetown, South Africa and delivered an invited talk entitled "Super Heavy Element and other Exotic Nuclei Research at LLNL".

M.A. Stoyer attended the 247th American Chemical Society Meeting in Dallas, TX March 15-19, 2014 and delivered an invited talk entitled "Recent Super Heavy Element Experiments" at a symposium in honor of Walter Loveland.

M.A. Stoyer attended the 3rd isotope harvesting at FRIB workshop held at Washington Univ. St. Louis May 4-7, 2014 and delivered an invited talk entitled "Isotope Harvesting Efforts at LLNL".

M.A. Stoyer attended the Exotic Beam Summer School (EBSS) held at ORNL July 29-Aug. 2, 2014 and delivered a lecture to approximately 45 students entitled "Nuclear Alchemy—The Sorcery of Synthesizing New Chemical Elements".

The funds also enabled M.A. Stoyer to chair the AGFA technical review committee held at Argonne National Laboratory in Aug. 2014 and the SHE collaboration meeting held at Texas A&M Univ. in Aug. 2014.

The funds also enabled participation in LBNL-led experiments to study the nuclear structure of the heaviest elements utilizing BGS coupled with γ-ray detectors. The ^{48}Ca + ^{243}Am reaction was studied, and 43 element-115 decay chains were observed that were in excellent agreement with our prior work at Dubna and recent experiments at GSI studying the same reaction [Gat14].

In addition, these funds enabled M.A. Stoyer to mentor a student. Sabrina Strauss, a student at the Univ. of Notre Dame, whose thesis advisor is Ani Aprahamian, has a Stewardship Science Academic Alliance fellowship which requires her to spend a 4 month practicum at a national laboratory studying a topic other than her thesis. She is spending her 4-month practicum at LLNL working on data analysis for a recent experiment performed in Dubna using the ^{48}Ca + ^{239}Pu reaction to look for lighter isotopes of Fl. In particular, she has written her own data analysis software and is extending the analysis to include the estimation of the probability that the decay chains observed in the data are merely due to a series of random events. She is using the Monte Carlo Random Probability techniques developed at LLNL [Sto00].

A list of recent publications and presentations is included below.

Articles

1. Investigation of the $^{243}Am+^{48}Ca$ reaction products previously observed in the experiments on elements 113, 115, and 117, Yu.Ts. Oganessian, F.Sh. Abdullin, S.N. Dmitriev, J.M. Gostic, J.H. Hamilton, R.A. Henderson, M.G. Itkis, K.J. Moody, A.N. Polyakov, A.V. Ramayya, J.B. Roberto, K.P. Rykaczewski, R.N. Sagaidak, D.A. Shaughnessy, I.V. Shirokovsky, M.A. Stoyer, N.J. Stoyer, V.G. Subbotin, A.M. Sukhov, Yu.S. Tsyganov, V.K. Utyonkov, A.A. Voinov, and G.K. Vostokin, Phys. Rev. C 87, 014302-1-10 (2013).

2. Synthesis and study of decay properties of the doubly magic nucleus ^{270}Hs in the $^{226}Ra+^{48}Ca$ reaction, Yu.Ts. Oganessian, V.K. Utyonkov, F.Sh. Abdullin, S.N. Dmitriev, R. Graeger, R.A. Henderson, M.G. Itkis, Yu.V. Lobanov, A.N. Mezentsev, K.J. Moody, S.L. Nelson, A.N. Polyakov, M. A. Ryabinin, R.N. Sagaidak, D.A. Shaughnessy, I.V. Shirokovsky, M.A. Stoyer, N.J. Stoyer, V.G. Subbotin, K. Subotic, A.M. Sukhov, Yu.S. Tsyganov, A. Türler, A.A. Voinov, G.K. Vostokin, P.A. Wilk, and A. Yakushev, Phys. Rev. C 87, 034605-1-8 (2013).

3. Experimental studies of the $^{249}Bk+^{48}Ca$ reaction including decay properties and excitation function for isotopes of element 117 and discovery of the new isotope ^{277}Mt, Yu.Ts. Oganessian, F.Sh. Abdullin, C. Alexander, J. Binder, R.A. Boll, S.N. Dmitriev, J. Ezold, K. Felker, J.M. Gostic, R.K. Grzywacz, J.H. Hamilton, R.A. Henderson, M.G. Itkis, K. Miernik, D. Miller, K.J. Moody, A.N. Polyakov, A.V. Ramayya, J.B. Roberto, M.A. Ryabinin, K.P. Rykaczewski, R.N. Sagaidak, D.A. Shaughnessy, I.V. Shirokovsky, M.V. Shumeiko, M.A. Stoyer, N.J. Stoyer, V.G. Subbotin, A.M. Sukhov, Yu.S. Tsyganov, V.K. Utyonkov, A.A. Voinov, and G.K. Vostokin, Phys. Rev. C 87, 054621-1-10 (2013).

Conference Proceedings

1. "New results for elements 115, 117, and 118 produced in the reactions $^{243}Am+^{48}Ca$ and $^{249}Bk/^{249}Cf+^{48}Ca$," V,K. Utyonkov, Yu. Ts. Oganessian, F. Sh. Abdullin, C. Alexander, J. Binder, R.A. Boll, S.N. Dmitriev, J. Ezold, K. Felker, J.M. Gostic, R.K. Grzywacz, J.H. Hamilton, R.A. Henderson, M.G. Itkis, K. Miernik, D. Miller, K.J. Moody, A.N. Polyakov, A.V. Ramayya, J.B. Roberto, M.A. Ryabinin, K.P. Rykaczewski, R.N. Sagaidak, D.A. Shaughnessy, I.V. Shirokovksy, M.V. Shumeiko, M.A. Stoyer, N.J. Stoyer, V.G. Subbotin, A.M. Sukhov, Yu. S. Tsyganov, A.A. Voinov, and G.K.Vostokin, 5th International Conference on Fission and Properties of Neutron-Rich Nuclei, eds. J.H. Hamilton and A.V. Ramayya, World Scientific: Singapore, (November, 2013) pp 278-285.

2. "New Insights into the Discoveries of Elements 113, 115 and 117" Y. Oganessian, F. Abdullin, S. Dmitriev, M. Itkis, A. Polyakov, R. Sagaidak, I. Shirokovsky, V. Subbotin,

A. Sukhov, Y. Tsyganov, V. Utyonkov, A. Voinov, G. Vostokin, J. Gostic, R. Henderson, K. Moody, D. Shaughnessy, M. Stoyer, N. Stoyer, J. H. Hamilton, A.V. Ramayya, J. Roberto and K. Rykaczewski, EXON 2012 Conference, eds. Yu. E. Penionzhkevich and Yu. G. Sobolev, World Scientific, 163-166 (2013).

3. "Study of the properties of the superheavy nuclei Z = 117 produced in the ^{249}Bk + ^{48}Ca reaction," Yu. Ts. Oganessian, F.Sh. Abdullin, C. Alexander, J. Binder, R.A. Boll, S.N. Dmitriev, J. Ezold, K. Felker, J.M. Gosic, "R.K. Grzywacz, J.H. Hamilton, R.A. Henderson, M.G. Itkis, K. Miernik, D. Miller, K.J. Moody, A.N. Polyakov, A.V. Ramayya, J.B. Roberto, M.A. Ryabinin, K.P. Rykaczewski, R.N. Sagaidak, D.A. Shaughnessy, I.V. Shirokovsky, M.V. Shumeiko, M.A. Stoyer, N.J. Stoyer, V.G. Subbotin, A.M. Sukhov, Yu.S. Tsyganov, V.K. Utyonkov, A.A. Voinov, and G.K. Vostokin, International Nuclear Physics Conference 2013 (Firenze, Italy), EPJ Web of Conferences 66, 02703 (4 pages) 2014.

4. "Production and Decay of the Heaviest Odd-Z Nuclei in the ^{249}Bk + ^{48}Ca Reaction," Yu. Ts. Oganessian, F. Sh. Abdullin, C. Alexander, J. Binder, R.A. Boll, S.N. Dmitriev, J. Ezole, F. Felker, J.M. Gostic, R.K. Grzywacz, J.H. Hamilton, R.A. Henderson, M.G. Itkis, K. Miernik, D. Miller, K.J. Moody, A.N. Polykov, A.V. Ramayya, J.B. Roberto, M.A. Ryabinin, K.P. Rykaczewski, R.N. Sagsaidak, D.A. Shaughnessy, I.V. Shirokovsky, M.V. Shumeiko, M.A. Stoyer, N.J. Stoyer, V.G. Subbotin, A.M. Sukhov, Yu. S. Tsyganov, V.K. Utyonkov, A.A. Voinov, and G.K. Vostokin, Proceedings 11th International Spring Seminar on Nuclear Physics, in press (2014).

5. "Connecting the "Hot Fusion Island" to the Nuclear Mainland: Search for ^{283,284,285}Fl decay chains, K. P. Rykaczewski, V. K. Utyonkov, N. T. Brewer, R. K. Grzywacz, K. Miernik, J. B. Roberto, Yu. Ts. Oganessian, A. N. Polyakov, Yu. S. Tsyganov, A. A. Voinov, F. Sh. Abdullin, S. N. Dmitriev, M. G. Itkis, A. V. Sabelnikov, R. N. Sagaidak, I. V. Shirokovsky, M. V. Shumeyko, V. G. Subbotin, A. M. Sukhov, G. K. Vostokin, J. H. Hamilton, R. A. Henderson and M. A. Stoyer, ARIS2014 Proceedings published electronically as a volume of the JPS Conference Proceedings (http://jpscp.jps.jp/).

Invited Talks by SHE Collaboration March 2013 - August 2014

1. M.A. Stoyer "Exploring the Limits of Nuclear Stability: Glimpsing the Island of Stability," invited talk at the American Association of Physics Teachers, July 16, 2013, Portland, OR.
2. M.A. Stoyer "Super Heavy Element and other Exotic Nuclei Research at LLNL," invited talk at the International African Symposium on Exotic Nuclei IASEN 2013, Dec. 2-6, 2013, Cape Town, South Africa.
3. M.A. Stoyer "Recent Super Heavy Element Experiments," invited talk at the 247th American Chemical Society National Meeting, March 16, 2014, Dallas, TX.

4. M.A. Stoyer "Nuclear Alchemy: The Sorcery of Synthesizing New Chemical Elements," lecture to University of California, Berkeley students April 9, 2014, Berkeley, CA.
5. M.A. Stoyer "Nuclear Alchemy: The Sorcery of Synthesizing New Chemical Elements," lecture to Exotic Beam Summer School students July 30, 2014, Oak Ridge, TN.

Future work

The complex interactions between nucleons will be probed by producing nuclei with the most nucleons in the nucleus. Exploration of the limits of nuclear stability (and chemical periodicity) will occur in collaboration with scientists at LBNL to strengthen both upper heavy element (SHE) scientific programs. Initial experiments led by LLNL will focus on new types of bolometer detectors used to detect SHE that have improved energy resolution compared with traditionally used Si detectors. Coupled with a time-of-flight system, this will enable measurement of masses to ≤ 1 amu in the A=300 region. Longer term innovative research in determining electronic configurations, constraining nuclear density functional theory and fission experiments will also be pursued.

What is the heaviest nucleus that can exist? This question has been at the center of nuclear physics for more than half a century. It remains one of the most fascinating and elusive open problems in nuclear physics and one that tests our fundamental understanding of nuclei. Over the past 15 years, six new elements with proton numbers Z=113-118 have been reported and much progress has been made to answer whether an "Island of Stability" exists for super heavy nuclei beyond uranium (92 protons). However, beyond basic nuclear decay information such as decay modes and half-lives, little else is known about these nuclei and there are many remaining questions. What are the limits of nuclear stability and chemical periodicity and how are the heaviest elements efficiently produced and observed in the laboratory? The goal of this project is to initiate a new program of experiments aimed at understanding the atomic and nuclear properties of the heaviest elements known to exist, utilizing the core scientific and technical capabilities of LLNL.

We specifically propose to: 1) obtain prototype, currently working bolometer detector arrays from Univ. of Mainz for rapid testing at the Center for Accelerator Mass Spectrometry (CAMS) with mono-energetic alpha particle and heavier ion beams; 2) optimize bolometric material, readout, thickness, size, operating temperature, and windowless design for improved energy resolution and increased detector efficiency; 3) design a time-of-flight (TOF) system and detector chamber including window for the back end of the Berkeley Gas-filled Separator (BGS) at LBNL; 4) construct an improved bolometer system at LLNL; 5) perform mass measurements; 6) interact with nuclear density functional theory (DFT) theorists at LLNL for improved calculations of mass in the SHE region and attempt to extend simulations to nuclear reaction predictions for SHE production. Longer term goals include 7) design and development of Stern-Gerlach experiments to investigate the electronic structure of heavy and superheavy nuclei; 8) design experiments to measure fission properties of the heaviest elements, including total kinetic energy (TKE) and mass distribution measurements crucial for nuclear fission theory developments. Post-doctoral researchers funded under this proposal will be involved in all areas of research. One may be stationed at LBNL to interface more effectively with scientists at LBNL, participate in LBNL led nuclear structure experiments, and to design and construct experimental apparatus to interface with BGS so that bolometry experiments can be performed.

It is anticipated that funds will be carried over into FY15 sufficient to ensure continued operation during October 2014. The future work described in this section is contingent upon funding of the proposal submitted in May 2014.

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